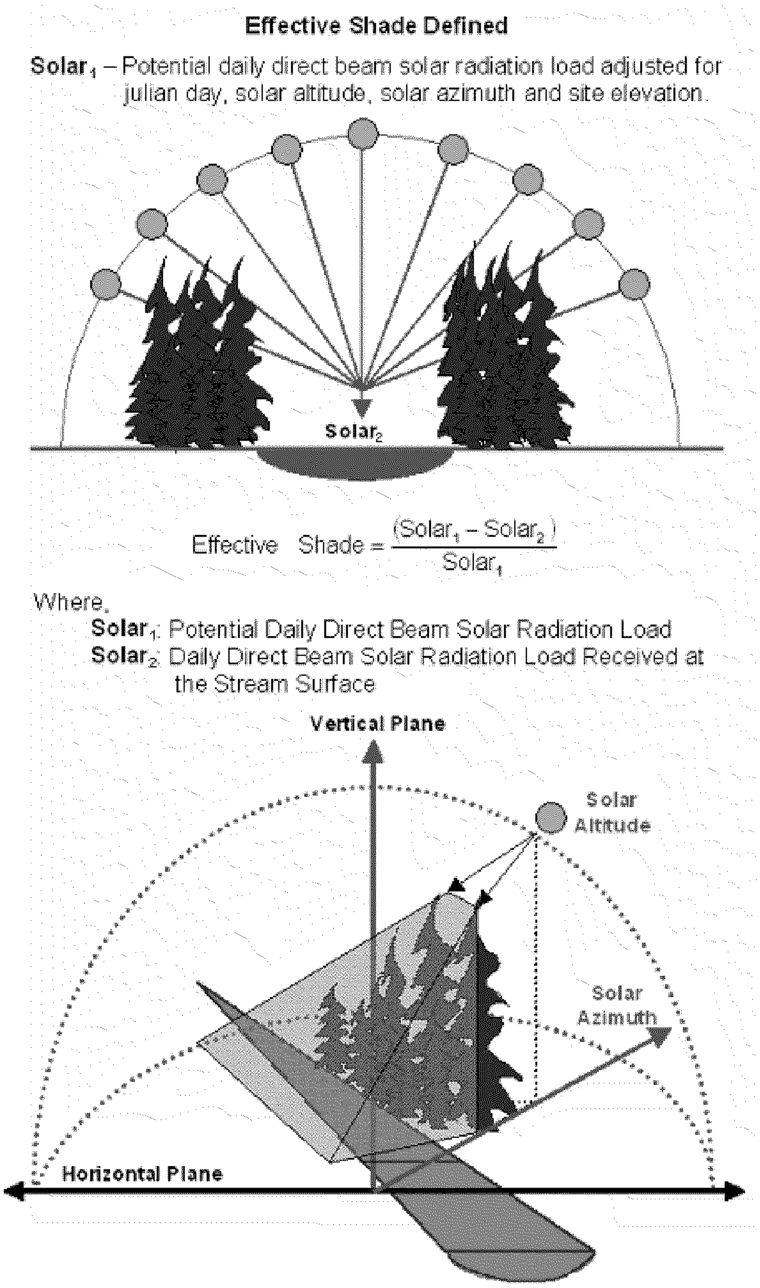
Defining the term 'vegetation density' as used in the model Heat Source.

Heat Source background. Heat Source is a model that can calculate stream temperature and heating rates at any given time of day as well as daily average heating. Heat Source calculates inputs including time-incremental (user defined, a typical time step is 1-minute) assessment of the amount of solar power reaching a stream based on the angle of incident sunlight (azimuth and altitude) and the amount of interception by vegetation and topography. Direct beam and diffuse (reflected from atmosphere, land cover and stream) solar radiation and long wave emission (also from atmosphere, land cover and stream) are calculated. Heat Source requires vegetation density to calculate the direct beam input, which in turn is used to calculate percent effective shade. Figure 1 defines the effective shade output from Heat Source[1].

Figure 1. Shade geometric relationships and effective shade defined



[1] Boyd, M., and Kasper, B. 2003. Analytical methods for dynamic open channel heat and mass transfer: Methodology for heat source model Version 7.0.

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Model vegetation and density inputs are developed and sampled in ArcGIS. A map of vegetation height and density values of stream side vegetation is developed either using LiDAR data or digitized vegetation polygons based on aerial photo interpretation. The stream centerline is digitized for each stream and segmented into 50-meter reaches separated by nodes. Starting from each stream node, the land cover (vegetation height and density) is sampled radially in seven directions at four user-defined (usually 15 m) intervals. Each sample is input to the model to represent a land cover zone (also referred to as vegetation zone). The model uses the land cover zone information to calculate effective shade.

Vegetation density. Along with vegetation height, vegetation density is a property assigned to a land cover. Vegetation density, expressed in percent, is directly related to the amount of direct beam solar radiation that is blocked as light passes through the vegetation. As such, vegetation density has a significant impact on shade results. However, the relationship is not linear, so that a change from zero to 25% vegetation density has much more of an impact on shade than a change from 75 to 100%. Vegetation density is a single value for each assessed land cover zone, independent of the direction of incoming sunlight. Ideally, it would be assessed as the afternoon average cross-sectional percent of light blocked through a rectangular box with the assessed face perpendicular to the solar vector. Another theoretical method to measure vegetation density would be to grid-count the light versus dark area of the shadow cast by vegetation, where the solar path length through the vegetation was equal to the user-specified zone width (usually 15 m).

We don't believe that the vegetation density (also referred to as land cover density) parameter in Heat Source has a direct equivalent to a field measurement. It appears to be related to terms used by land management agencies like angular canopy density, canopy cover and crown cover (see Table 1). In practice, vegetation density has been based on various types of estimates, such as canopy density assessed through aerial photographs or a relationship to solar pathfinder readings or visual estimates based on observations of tree shadows. However, field measurements sum all the densities from the variety of vegetation types in the solar path (it does not separate vegetation densities by land cover zones), whereas the model calculates the impact of each land cover zone and then calculates the cumulative impact. Also, vegetation density is regularly varied based on the resolution of the vegetation map (whether each tree is represented or whether a stand is represented).

Math behind shade calculations. The math behind calculations of solar radiation are as follows (simplified from the

Heat Source manual, Version 7.0[1], page 43):

When the sun is being obscured by vegetation alone, then solar radiation is reduced by the following formulation, for each applicable vegetation zone (based on Beer's Law):

Where:
PL: path length (the distance light travels through the vegetation zone)
W: width of the vegetation zone
θ_{SA}: solar altitude
Ψ: shade density (unitless) (cumulative fraction of solar radiation blocked)
VD: vegetation density (%)
Φ: direct beam solar radiation (e.g., W/m^2)

Note that it is both the vegetation density and the width of land cover zone that impact the amount of solar radiation blocked. Therefore, a land cover zone that is 15 meters wide will block more solar radiation than a zone 5 meters wide with the same vegetation density. One way to simplify this might be to represent percent of solar blocked per meter, so the land cover zone width would not impact the vegetation density.

Figures to further describe vegetation density. The following figures are provided to illustrate the influence of vegetation density in various scenarios.

Figure 2. Direct beam solar radiation, after atmospheric processes.

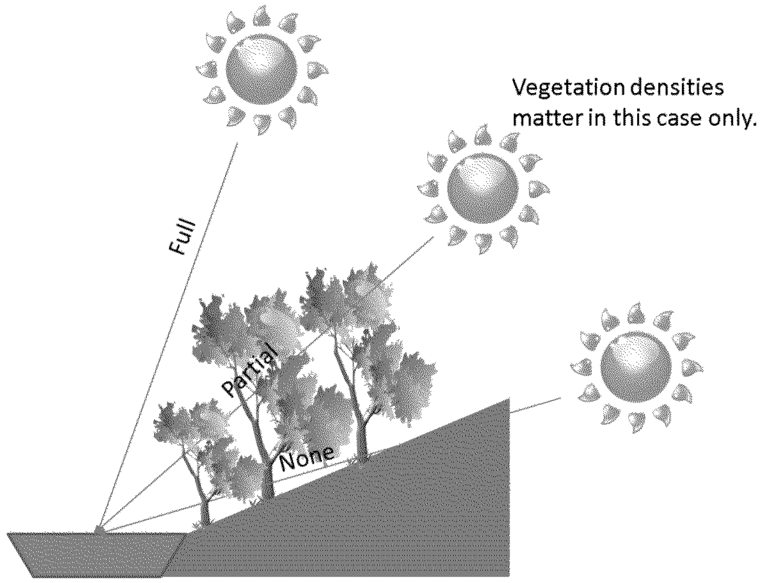


Figure 3. Example of the cumulative solar radiation blocked (Ψ) (cumulative amount of direct beam solar radiation that does not pass as light through the vegetation zones) at the edge of each land cover zone based on given vegetation height and density (density reported below each zone), land cover zone width = 15m, and solar altitude = 45°.

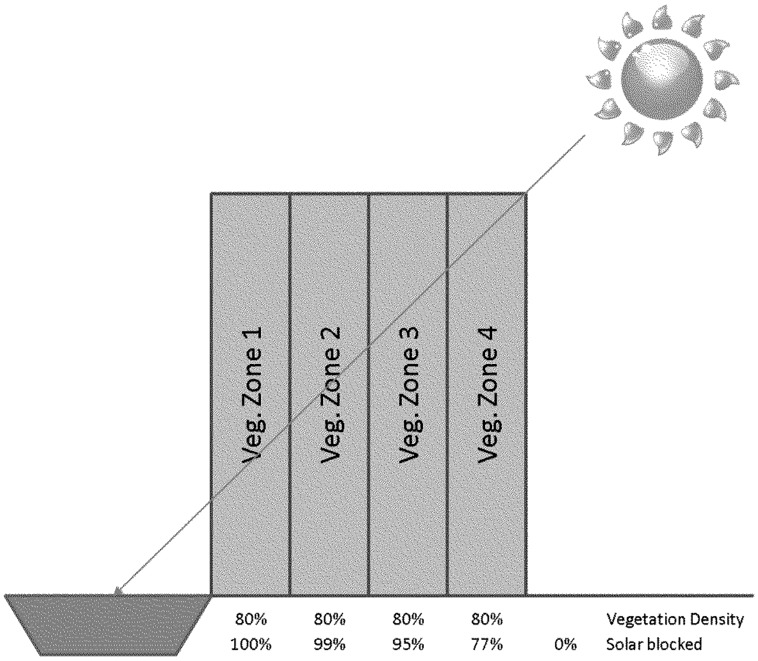
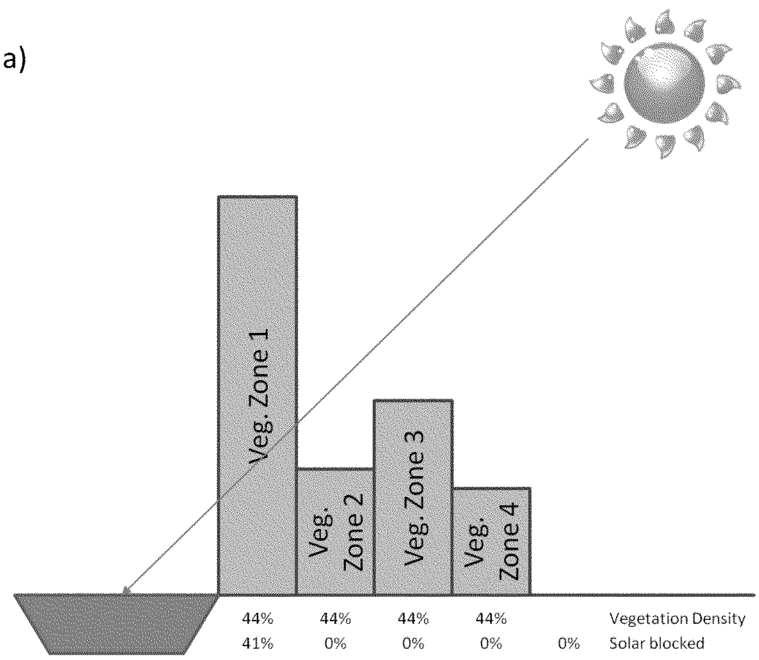


Figure 4 'a' and 'b'. Figures 4 and 5 illustrate that the aggregate density model calculation is a function of height as well as density. Example of the cumulative solar radiation blocked (Ψ) (cumulative amount of direct beam solar radiation that does not pass as light through the vegetation zones) at the edge of each land cover zone based on vegetation height and density (density reported below each zone), land cover zone width = 15m, and solar altitude = 45°. Both examples 'a' and 'b' have the same cumulative solar radiation blocked. Example 'a' could be thought of as a high resolution land cover data set while 'b' could be thought of as a lower resolution land cover data set.

a)



b)

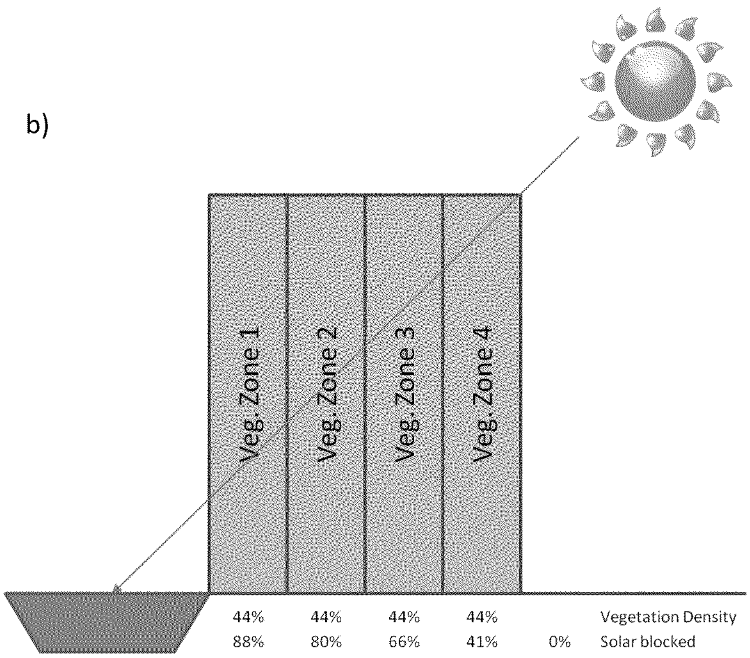
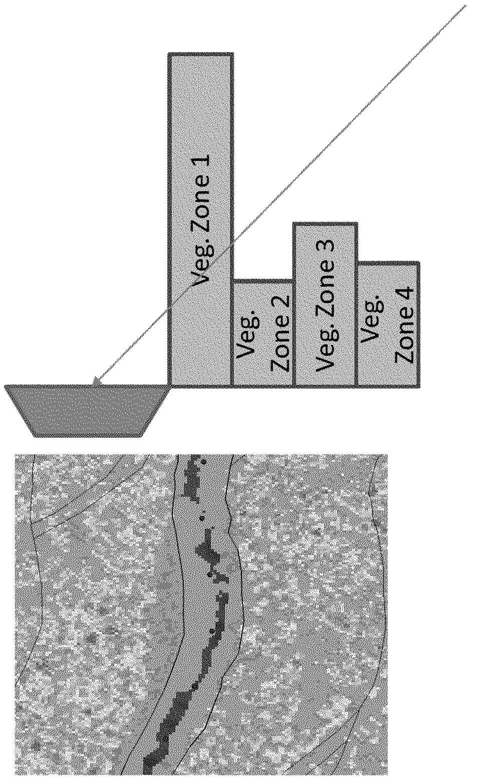
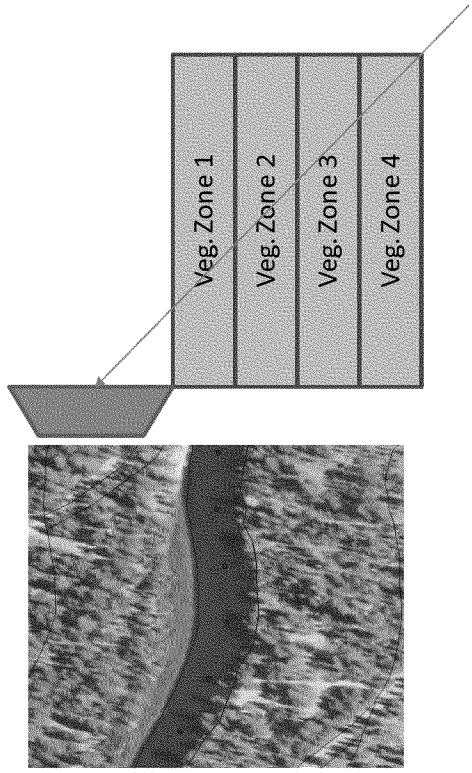

Veg. Zone 1
Veg. Zone 2
Veg. Zone 3
Veg. Zone 4
44% 44% 44% 44% Vegetation Density
88% 80% 66% 41% 0% Solar blocked

Figure 5. Example visualization of different land cover resolutions changing how heights are sampled in each land cover zone, though the densities remain the same. This changes the amount of solar radiation blocked (Ψ). Colors in the image on the lower left represent vegetation heights (grey = 0m to teal = 39-52m) The polygons in the image on the lower right represent areas of similar land cover type and are provided in the lower, left image for reference only. The two schematic in the upper portion are not actual representations.



Vegetation Heights from LiDAR



Vegetation Polygons from aerial photo

Figure 6. Figure 6 illustrates the effect of land cover zone width on the cumulative solar radiation blocked (Ψ) (cumulative amount of direct beam solar radiation that does not pass as light through the vegetation zones) at the edge of each land cover zone based on vegetation density (reported below each zone), land cover zone width = 5 m, and solar altitude = 45°. The width of the land cover zone has been decreased to 5 meters rather than 15 meters as shown in the from previous examples.

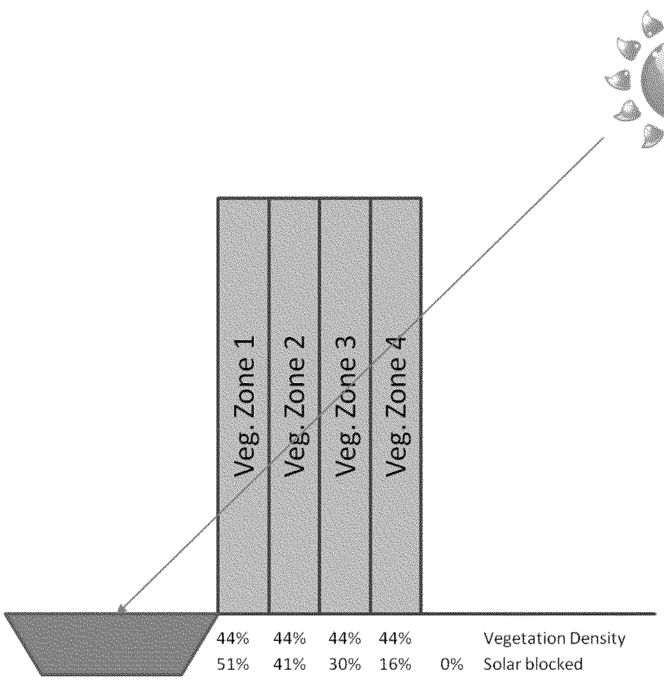


Figure 7. This figure illustrates the sensitivity of effective shade results to vegetation density inputs. All examples are from Whychus Creek using the same spatially varying vegetation height and topographic shade. Vegetation was digitized as polygons from aerial photographs. In this example, only vegetation density was changed, leading to a wide array of model outputs. The effective shade results are shown as the 1km moving average. Effective shade is inversely proportional solar heat flux.

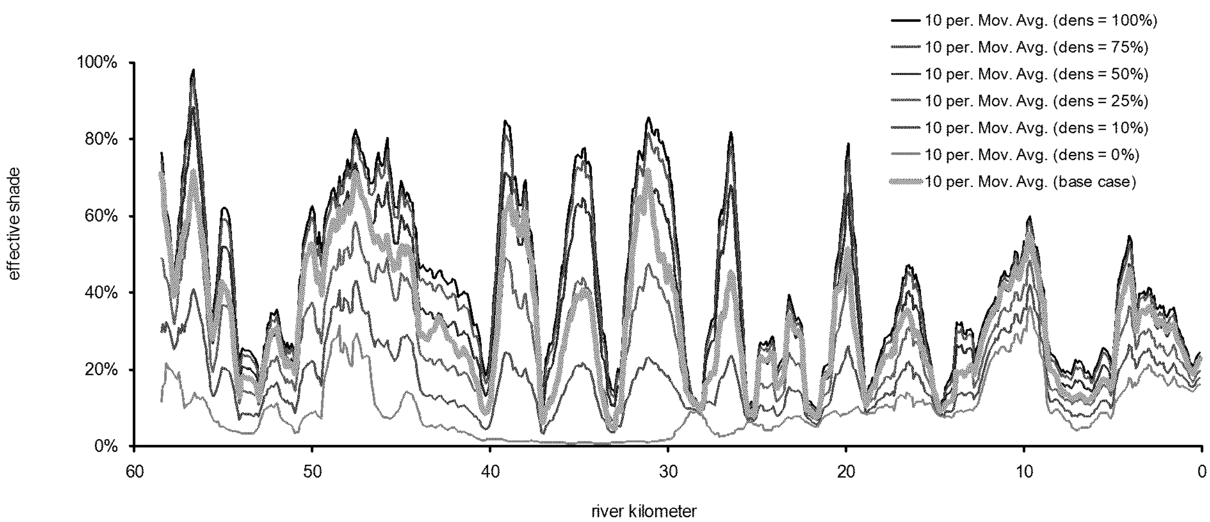


Table 1. Metrics related to vegetation density (pers. comm. Eric Pfeifer, USFS 2011)

Metric	Notes
Basal area	Probably the poorest surrogate of this group, as basal area is a direct measurement of stem density (the average cross-sectional area of tree stems within a given area). It's roughly related to canopy density, but mostly within a given range (after canopy closure, basal area can continue to increase). Can be readily measured in the field across large areas.
Stand density index	A measure of stem density similar in nature to basal area, with similar advantages and disadvantages.
Percent canopy cover	Could be assessed in the field with a densitometer, but many samples would be needed. Might be a good fit if utilized in conjunction with aerial photos for cross-validation.
Leaf area index	A description of the cumulative shade density of the total vegetation profile, as it is a direct measurement of incoming solar radiation (watts / M^2). LAI is a measurement of the surface area of vegetation leaves per unit of ground area across a vertical profile. For example, a canopy with an LAI of 2.0 would be 2 meters of leaf area per meter of ground area. I'm not sure how appropriate LAI would be as a model input since it represents the cumulative effect of potentially multiple land cover zones. Nonetheless, if LAI could be measured/calculated for individual zones, it might be a good surrogate. (one tool: http://www.licor.com/env/products/area_meters/LAI-2200/)
Aerial photo interpretation of vegetation density and height	For modeling purposes, this is probably the best approach, since it can offer a degree of spatially-explicit vegetation density assessment, and much less expensive to gather. Although this method wouldn't measure true canopy density very well after canopy closure, it might be useful for land cover zones with canopy density of 0-100%. Also, vegetation height can be assessed (if lumped into broad categories) using a stereoscope. If measurements for height categories and land cover types could be taken in the field, broad categories could be derived from the field measurements and applied across a landscape using aerial photos.